Embedding of fibre optic sensors within flexible host

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Abstract

This work deals with the establishment of a UV polymerisation procedure combined with moulding technology towards the development of a mass production technology for the fabrication of flexible polymers with optical fibres embedded. The concept is to provide an artificial sensing skin based on fibre optic sensors which can be applied to irregular or moveable surfaces for distributed pressure applications, as for instance in structural monitoring or rehabilitation. The selected polymers for such an application are here reviewed and their composition adjusted in order to accommodate the required flexibility. As compared to other techniques, UV polymerisation advantages are pointed out when moving towards industrial applications and large scale productions. Meanwhile, curing tests to embed optical fibres in the developed polymers are carried out with an in house developed glass mould set-up and the results are presented. Laser ablation of polymers is also discussed in order to reply the demand of complex fibre layout as for example meandering or curved shape patterns.

Keywords: fibre-optic sensors, methacrylates, UV polymerisation, laser ablation, micromachining

1. Introduction

Optical sensors are very attractive for a wide range of applications within automation, aviation, structural monitoring, and robotics. They offer several advantages, not only because of their immunity to electromagnetic interferences (EMI), but also thanks to their resistance to harsh environments, high sensitivity and potential parallelizing of the readout. Therefore, new concepts of sensors for strain, pressure, and temperature can be conceived.

One recent challenge is the development of a flexible foil in which fibre optic sensors are embedded and integrated with the light sources, detectors and electronic circuitry onto a compact signal processing board [1]. Then, the foil can be applied either to irregular or moveable surfaces for distributed pressure sensing applications. Moreover, it can be folded into compact modules as for portable devices.

The realisation of such an optical sensing skin poses new demands. First, flexible substrates are necessary. Ideally, the carrier should be both elastic and stretchable in order to follow movements and deformations of the surfaces on which it is mounted. Considering standard silica glass fibres, the sensors themselves will never be stretchable. Therefore, new embedding strategies and compliance fibre layout must be also investigated. Moreover, good adhesion among the substrate and sensing elements is crucial. Furthermore, a reliable and cost-effective manufacturing technology must be developed for embedding, aligning and positioning optoelectronic components and fibres over flexible parts without jeopardizing their optical performances and coupling efficiency.

In this work, examples of suitable materials for such an artificial sensing skin are provided, and their composition tuned to achieve the required flexibility. In addition, a UV polymerisation procedure combined with moulding technology is conceived and tested towards the development of a cost effective and reliable mass production technology. To cope with the requirement of complex fibre layout embedding, laser ablation of polymers is also investigated.

2. Material development

The selected monomers for the development of flexible substrates for optical sensor applications are depicted in Figure 1. The selection was based on the ability to adjust the mechanical properties of the materials as well their chemical resemblance with commercial packaging (e.g. Truemode^{TM}) and fibre coatings (polymethacrylate based materials) materials. In order to widen the application range, including rehabilitations and medical solutions, the material biocompatibility was also taken into account.

The (co-)polymers were produced using a classical solution radical polymerization (see also next section); the results were then characterised by recording the characteristic spectra and temperatures. A correlation between the theoretical and experimental composition within ± 5mol% was obtained (Table 1). By partially replacing MMA with BuMA or EHMA, the glass transition temperature decreased, which is in favour of an increasing flexibility. This effect was more

pronounced when using EHMA (Table 2), and a pre-selection could be made. All materials developed were stable up to 220-230℃, which is far above the standard working conditions of a wide range of the envisaged applications. For details on production and characterisation methods, the authors refer to [2].

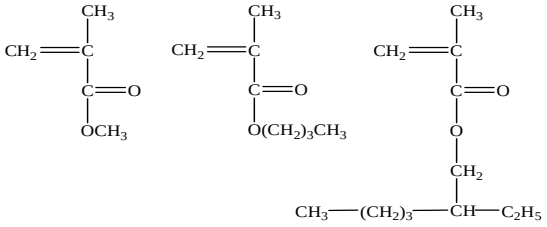

Figure1. From left to right, chemical structure of methyl methacrylate (MMA), butyl methacrylate (BuMA), 2-ethylhexyl methacrylate (EHMA)

Table1. Theoretical vs experimental composition of the copolymers developed

	Theoretical composition(mol%)	Experimental composition(mol%)
TVG1	MMA/BuMA80/20	MMA/BuMA75/25
TVG2	MMA/BuMA50/50	MMA/BuMA42/48
TVG3	MMA/BuMA20/80	MMA/BuMA24/76
TVG4	MMA/EHMA80/20	MMA/EHMA79/21
TVG5	MMA/EHMA50/50	MMA/EHMA51/49
TVG6	MMA/EHMA20/80	MMA/EHMA21/79

Table2. Glass transition temperature (T_g) and decomposition temperature (T_{decomp}) of the materials developed

Code	T_g (℃)	T_{decomp} (℃)
TVG1	96	228
TVG2	66	231
TVG3	51	---
TVG4	51	222
TVG5	29	230
TVG6	- 4	229

3. UV polymerisation

To effectively polymerize and shape foils based on methacrylates polymers, a UV curing procedure combined with moulding technology was developed and tested.

When moving towards industrial applications, UV polymerisation is expected to provide mayor benefits. As compared to other techniques, the procedure complexity reduces considerably. In the case of injection moulding, for instance, the materials in question would be made by means of classical solution radical polymerization, according to the following protocol.

- Monomer is dissolved in toluene, yielding a monomer concentration of 1.7 - 1.8 M, which is mostly applied to perform radical solution polymerizations.
- While stirring, the set-up is degassed up to 3 times to remove oxygen which can inhibit the polymerization reaction.

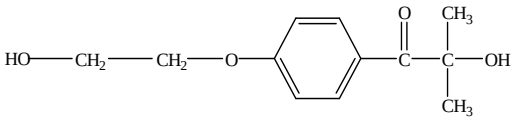

Figure 2: Chemical structure of the photo-initiator Irgacure 2959

- The desired amount of thermal initiator (AIBN) is added as a solution in toluene.
- The mixture is degassed at least once more, and the reaction is kept 24 h under N_2 atmosphere at a temperature of ca. 75℃ under continuous stirring, to assure the radical generation of the initiator.
- The polymer is then isolated by precipitating the polymer formed in a 10 fold excess of ice-cooled non-solvent, and the residue separated by filtration.
- The polymer is dried under vacuum at the oil pump, purified by means of repeated redissolution and precipitation, and dried again.

The procedure is very time consuming and may take up to several days, which is a major drawback when moving towards a large scale production. On the contrary, the experience demonstrated that UV induced mass polymerization of foils 1 mm thick may take up to 1 hour 30 minutes depending on the type of methacrylate to polymerize. Moreover, as shown by ^{1}H-NMR analysis of the produced materials, UV-polymerisation took place in one single shot, and complete conversion could be achieved during curing. Furthermore, as a consequence of the restricted number of factors influencing the reaction, the process is highly reproducible. In contrast, polymer films made by means of solution polymerization and injection moulding will always have a certain variation in molecular weight. On the other hand, in case of UV-polymerisation, the reaction conditions (i.e. irradiation time) have to be optimized each time the composition of the material changes.

When moving to UV-cured polymethacrylates, biocompatible materials can easily be obtained. Up to now, combinations of the monomers methyl methacrylate, butyl methacrylate, 2-ethylhexyl methacrylate were tested with Irgacure 2959 (Figure 2) as the photo-initiator. Since the polymer materials and initiation system both have a proven biocompatibility, the obtained foils will be most likely biocompatible too, and one can expect that no further steps will be required to achieve the requirement. [3]

Finally, the UV curing system can be easily up scaled to larger size and larger quantity, while maintaining the production time and investment effort limited. To achieve this, a larger light source could be used and a continuous set-up could be worked out.

Preliminary tests to embed fibres in the polymers developed were carried out with an in house developed mould set-up. Glass was selected as mould material as being UV transparent, chemical inert and easy to clean. Indeed, the adoption of standard mould materials, e.g. PMMA, would concur to a strong interaction between the sample and mould material, while any other plastic would greatly affect the UV absorption coefficient of the system set-up. On the other hand, glass machining by traditional cutting process is prevented owing to its high hardness, and

special processes are required. At the moment, Ultra Sonic Machining (USM) is being applied [4]. Additional technologies, such as glass etching and glass moulding, will be also investigated in the near future to reach a wider machining flexibility.

3.1. Moulding tests

As first moulding test, cylindrically substrates with a fibre embedded were produced. The aim is to produce suitable samples for performing adhesion and non destructive optical sensitive tests [5].

A glass mould as sketched in Figure 3 was produced [2].

It consists of two screwed glass plates with a cylindrical cavity, 2 mm in diameter and 1 cm in length. Two ferrules in titanium alloy (grade V) are inserted to accurately position the optical fibre (standard coated optical fibre 0.250 mm in diameter) into the cavity and to allow the injection of the monomer/initiator mixture through an apposite hole. Titanium was selected because of its chemical resemblance with the pre-and post-irradiation treatments envisaged.

Since the viscosity of reaction mixture is very low, the sealing of the mould required particular attention. Hence, silicon UV resistant o-rings were positioned at the ferrule-glass interfaces to avoid leakage.

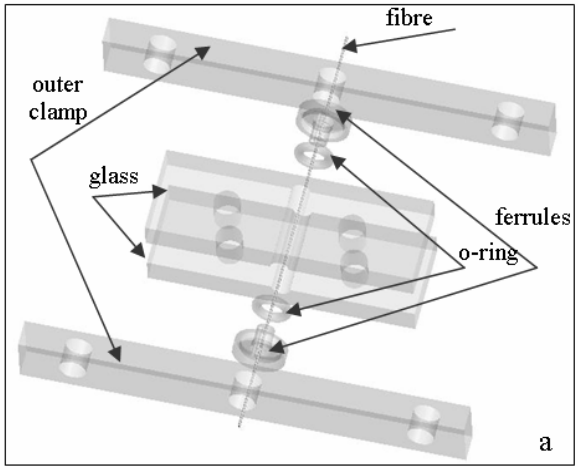

Figure 3 Exploded view of the mould layout

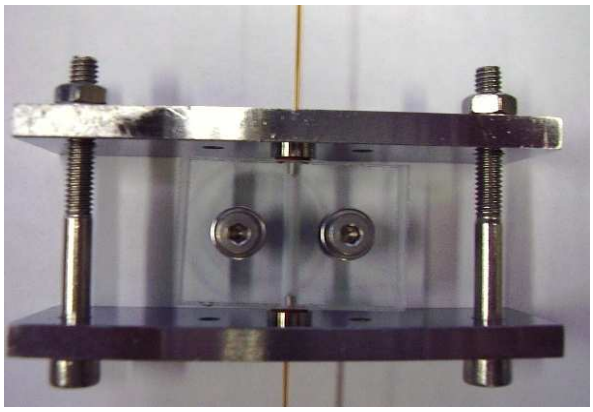

Figure 4 Image of the mould during employment

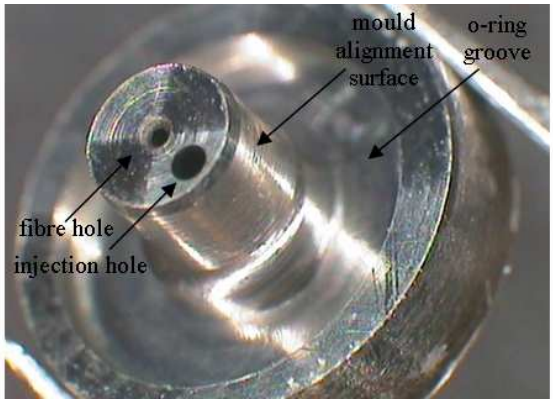

Figure 5: Image of the ferrule realized in titanium

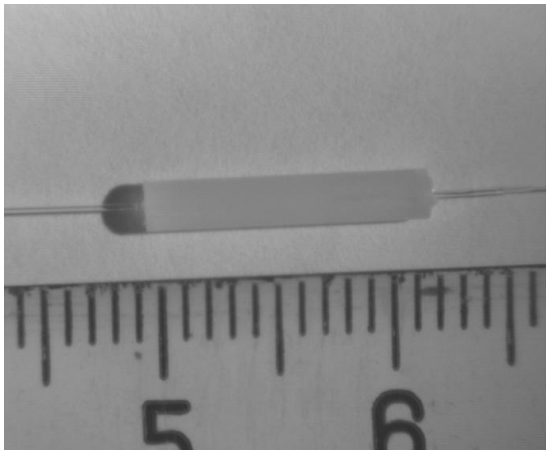

Figure 6: Picture of a UV cured polymethacrylate tube with an optical fiber embedded

Additionally, micro tubes were pressed fit into the injection holes and used as reservoirs. The mould was finally tightened by means of a dedicated outer clamp (Figure 4).

Each mould component/feature was manufactured by using the most adequate technology.

The glass plates were cut to length with a diamond tool, then polished and drilled by ultrasonic milling on a Sauer75-USM centre. A dedicated tubular tool coated with diamond abrasive particles (grit size D96) was used to drill the cylindrical cavity and the screw holes. The spindle rotation was 4500 RPM and the feed rate set to 4 mm/s. Meanwhile, cylindrical blanks with diameter of 6 mm were cut by wire-EDM (electro discharge machining) on a Robofil-Charmilles centre, and machined on a precision Hembrug lathe into the outer shape of the ferrules. The tolerance achieved was within 0/+5 μm. The components were then clamped on a 5-axis Kern MMP 2522 micromilling centre to mill the o-ring grooves. Since the total length of the inserts is 3 mm, the fibre alignment hole (ø 0.25mm 0/+ 5 μm) with tapered entrance, and the mixture injection hole (ø 0.5 mm) were finally realised by EDM drilling on a 4-axis SARIX SX-100-HPM micro-EDM centre [5] to cope with their high aspect ratio. A finished component is shown in Figure 5.

Fabrication tests were performed using a mixture of methyl methacrylate and Irgacure 2959 as the photo-initiator. After dissolution of the photo-initiator in the monomer, the mixture was cured using UV-light with a wavelength of 365 nm and an intensity of 15 mW/cm^2. The test set-up was then irradiated for 2 hours. Before injecting the reaction mixture into the mould, the glass material was also treated with release spray to ensure proper sample release. Different cavity orientations and injection conditions were applied before achieving optimal results. Specifically, when both injection of the reaction mixture and irradiation were carried out with the axis of the cylinder in vertical orientation, samples with the desired shape and dimensions could be obtained (Figure 6). This position maximizes the efficiency of the reservoirs and keeps the liquid mixture degassed. Provisional characterization of the samples with a micrometer showed that the polymer cylinder has a length of 123 mm and a diameter of 2.05 mm. Further characterisation (e.g. fibre straightness and position accuracy) is currently ongoing.

4 Laser structuring

Fibre optic sensors are not stretchable themselves. Therefore, in order to provide an optical sensing foil which is elastic in whole, the embedding of compliant fibre layouts as for instance meandering or curved shaped patterns must be considered. As efficient embedding method, laser structuring of polymers was investigated. The idea is to export the desired 2D fibre layout from a CAD sketch to a laser drilling file, and directly write the pattern onto the hosting sample. Afterwards, the fibre can be fixed within those tracks and glued with a primer in order to ensure optimal adhesion. The embedding can be finally completed by casting an upper hosting layer.

At CMST 3 lasers, integrated in one laser system, are available. It consists of a KrF Excimer, a Nd-YAG and a CO_2 laser. Specifically, the CO_2 laser (of properties as depicted in Table 3) was proven to be the most appropriate to ablate silicone samples (Dow Corning, Sylgard® 184), as the stretchable hosting.

Experiments were performed to make the best structured track. This resulted in a pulse frequency of 100 Hz and an ablation speed of 8.7 mm/s together with minimal power attenuation (maximum pulse energy). A result of a meandering fibre embedded is shown in Figure 7.

5. Conclusions

A series of methacrylate based copolymers for the development of flexible foils with fibre-optic sensors embedded were developed and their composition was tuned to accommodate the desired flexibility. The T_g drastically decreased for EHMA based methacrylates; based on this result a provisional selection of the suitable material can be made. A UV polymerisation procedure combined with moulding technology was established towards the development of a cost effective and reliable mass production technology. The feasibility was successively proved when embedding optical fibres within methacrylates based polymer tubes as the suitable samples for adhesion and optical sensitive tests. Additionally, laser ablation of polymers was investigated and applied to thermal curable polymers to embedded horseshoe shaped fibre layout. The results are currently being transferred to the UV curable polymers developed for the certain purpose.

Table 1: CO_2 laser parameters

Parameters	Value
Wavelength	10.6 µm
Pulse duration	70 ns
Max. pulse energy	400 mJ
Max. pulse frequency	150 Hz

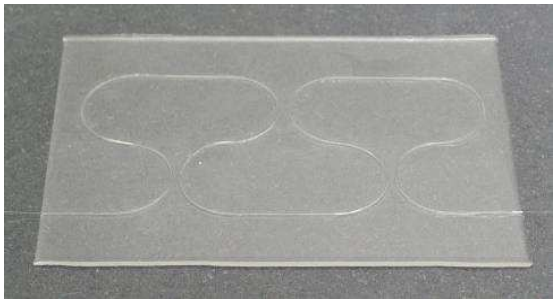

Figure 7: standard silica glass fiber embedded in a meandering shape within the Sylgard® 184 stretchable silicone by using laser ablation

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